ADVISOR MODEL OF THE HONDA INSIGHT

Introduction

Based on analysis of test data from the Honda Insight, a model in NREL's ADVISOR (**AD**vanced **V**eh**I**cle **S**imulat**OR**) was developed. Test data from the National Renewable Energy Laboratory (NREL) and Argonne National Laboratory (ANL) were used in the analysis. The aim of the model is to predict the control actions performed on the various components of the drivetrain (engine, electric motor, batteries etc.). The following major observed phenomena are modeled.

The electric motor of Honda's Integrated Motor Assist (IMA) provides approximately 10 Nm of assist in most cases when a large torque (approximately >20 Nm) is commanded of the vehicle (This is physically interpreted as an indication for acceleration through depressing the accelerator pedal). An exception is when the vehicle is in first gear, wherein the motor does not assist the engine.

The electric motor of the IMA performs regeneration when the vehicle slows down, as there is torque from the inertia of the vehicle coming into the driveline. When the brakes are depressed, there is heavy deceleration, and a lot of negative regenerative torque is seen at the driveline. The controller senses the braking, and allows the motor to capture a part of that energy back into the battery. This ensures that the battery is charged and all energy is not lost in the form of heat. During braking, a small portion of the braking force is provided by the electric motor, and the remaining part from the friction brakes.

Using the above concepts, a ***scalable controller*** was developed and incorporated into ADVISOR, which allows for simulating the entire Insight drivetrain on the computer. The model was developed as Simulink blocks, which can be used by ADVISOR.

Vehicle Model

The Insight base block uses a "direct split" of the torque signal, whereby the controller directly commands the torque from the two power sources, unlike the default parallel hybrid strategy. In the default strategy, the entire driving torque is requested from the IC engine, and the dearth of torque (unmet torque) is demanded from the electric motor (a feedback loop is constructed in the torque coupler). Here, there is a separate torque command sent to the electric motor, from the control strategy. This makes sure that the components provide the correct amount of torque commanded by the controller. The torque converter is used for summing the two torques and sending them back to the gear box. (No feedback is performed to the control strategy, based on the individual power sources).

The base Insight Simulink model is shown in Figure 1.

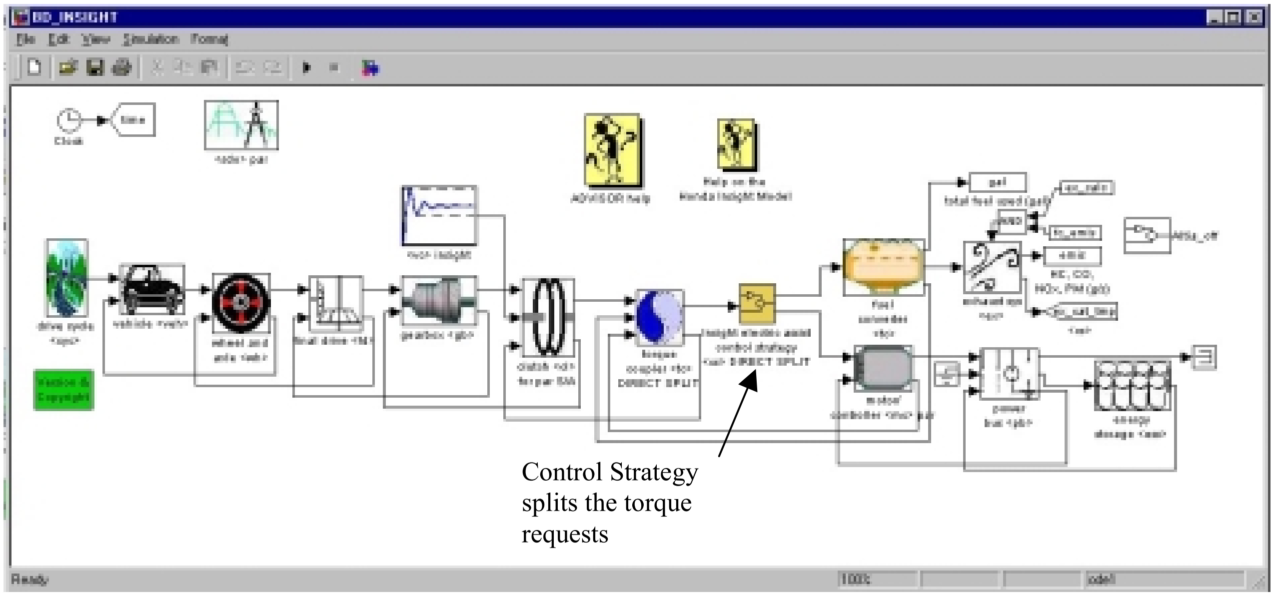


Figure 1: Base block diagram of the Insight in ADVISOR

Changes to the Insight model

The following changes were made to the Insight model in ADVISOR.

1. A new ***scalable*** Torque-Split Control Strategy based on test data analysis (block shown in Figure 1).
2. Engine on-off control was added (previously included in ADVISOR 3.0).
3. Usage of engine fuel-use map data, based on vehicle component testing by Argonne National Laboratory (ANL).
4. State of charge correction strategy.
5. Documentation is added on the use of the scalable strategy.

The scalable control strategy

Based on the working of the Insight, a scalable control strategy was developed in ADVISOR. This strategy is very flexible in its parameters, and a user can use the new strategy for designing his own new controller. It also provides for conducting sensitivity analysis on parameters.

Figure 2 shows a schematic of the structure of the controller, and the variables used in defining such a system. The variables can be defined before simulation and can be changed independently, for altering the functionality of the electric motor.

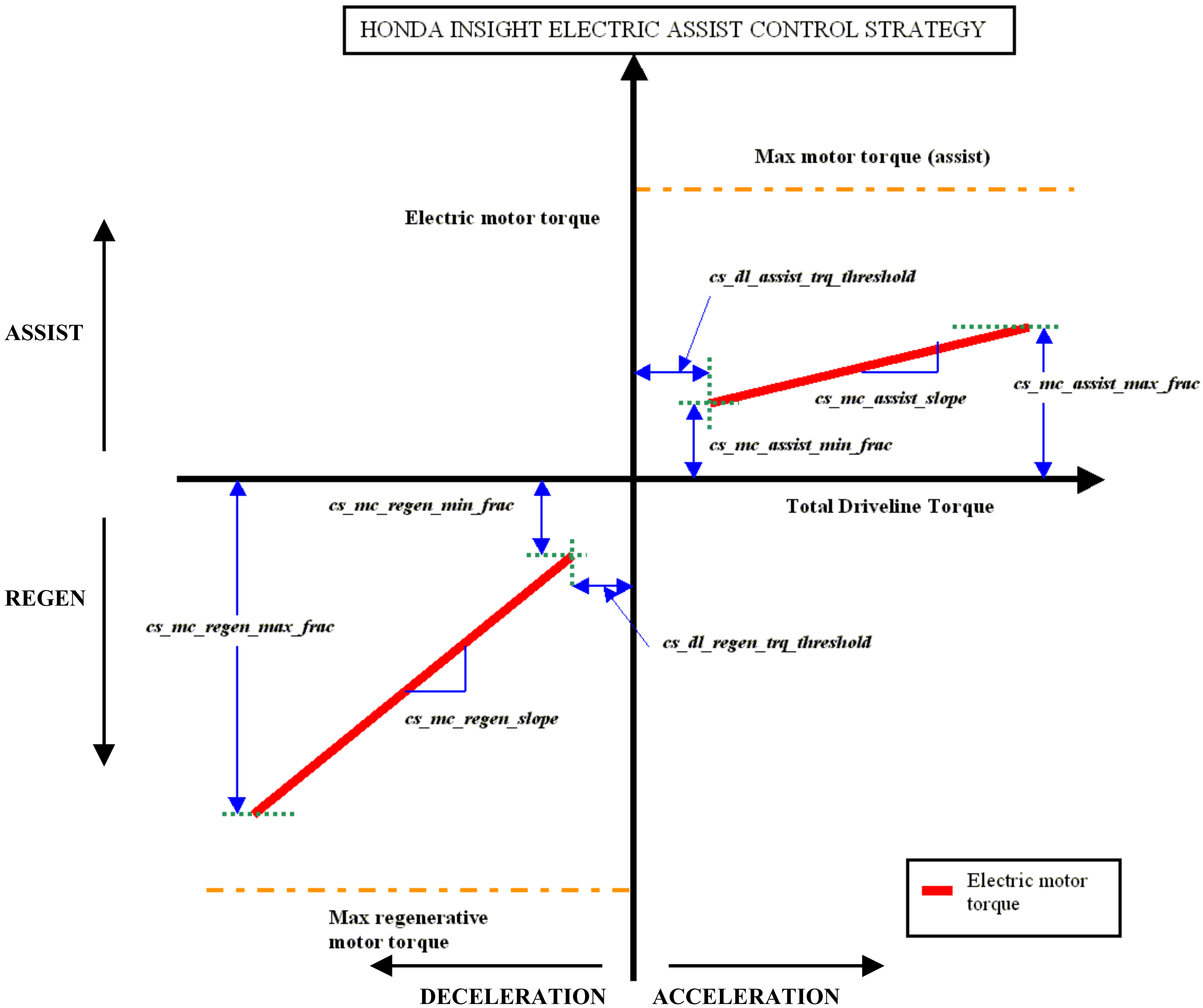


Figure 2: Scalable control strategy structure

In the above diagram, the parameters shown are used in determining the behavior of the electric motor, based on the vehicle torque demand. The solid RED line in the upper right quadrant of the graph defines the level of assist provided by the electric motor. When the driveline torque required exceeds the parameter *"cs_dl_assist_trq_threshold,"* the motor provides assist, starting at a level indicated by *"cs_mc_assist_min_frac,"* and increases according to the parameter *"cs_mc_assist_slope,"* which indicates how much assist the motor should provide, based on the driveline torque. The maximum assist of the motor can be limited by using the parameter *"cs_mc_assist_max_frac."* The motor torque limits are represented as a fraction of the max torque capacity of the motor.

Similarly, the solid RED line in the lower left quadrant defines the level of regeneration provided by the electric motor. When regenerative torques seen by the driveline exceed the parameter *"cs_dl_min_trq_threshold,"* the motor starts regenerating with a minimum value equal to *"cs_mc_regen_min_frac,"* and increases according to *"cs_mc_regen_slope."* This parameter defines the amount of regen the motor provides, based on what is seen at the driveline. As in the case of assist, motor regen torque can be limited using the parameter *"cs_mc_regen_max_frac."* These limits are a function of the maximum regenerative capacity of the motor.

Table 1 provides a summary of the parameters used in this scalable control strategy. For the Insight, the parameters were chosen based on actual test data from various driving cycles.

Table 1: Summary of parameters used in the scalable control strategy

Variable	Description
cs_dl_assist_trq_threshold	Driveline torque threshold below which the electric machine does not assist
cs_mc_assist_min_frac	Minimum torque normally provided by the electric motor when driveline torque exceeds threshold (as a fraction of max torque)
cs_mc_assist_slope	Fraction (slope of the line) of the driveline torque provided by the electric motor when the driveline torque exceeds threshold
cs_mc_assist_max_frac	Maximum motor torque requested from the motor during assist (as a fraction of max torque)
cs_dl_regen_trq_threshold	Driveline regenerative torque threshold above which the electric machine does not regen at low speeds
cs_mc_regen_min_frac	Minimum regen torque normally provided by the electric motor when driveline torque exceeds regen threshold (as a fraction of max regen torque)
cs_mc_regen_slope	Fraction (slope of the line) of the negative driveline torque regenerated by the electric motor when the driveline torque exceeds threshold
cs_mc_regen_max_frac	Maximum regen motor torque requested from the motor during regeneration/braking (as a fraction of max regen torque)
cs_decel_regen_threshold	Speed during deceleration below which the electric motor does not regenerate (all emphasis on friction braking)

The controller block

The Insight parallel hybrid controller block, used to implement the above structure is shown in Figure 3.

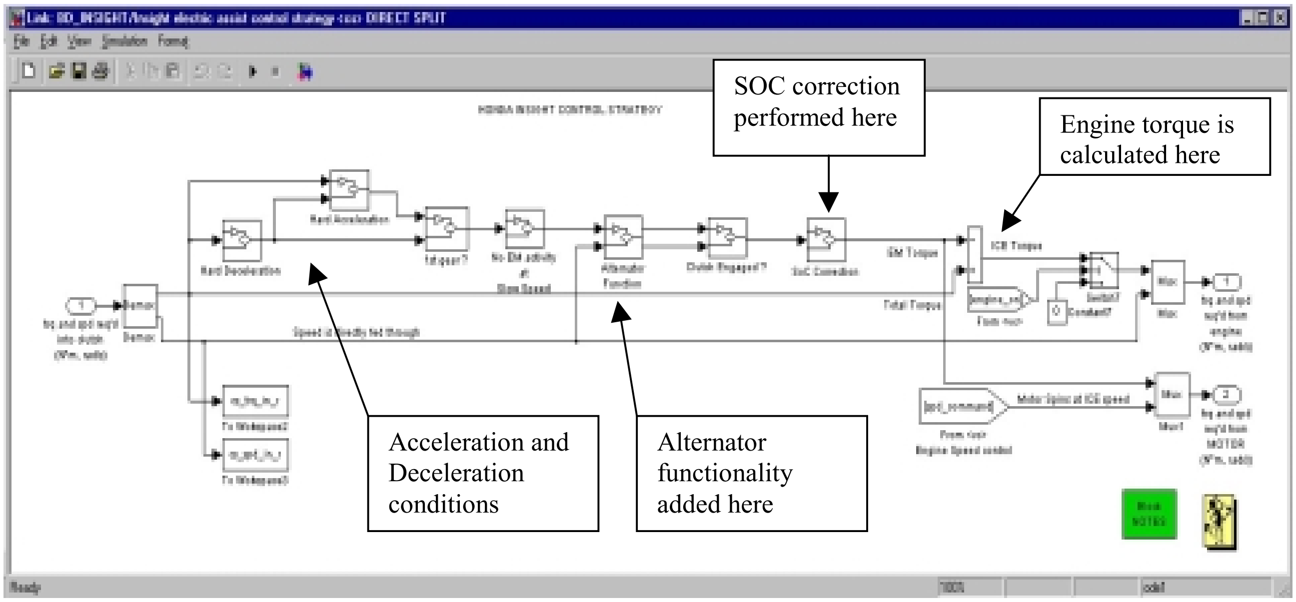


Figure 3: Insight control block in ADVISOR

The controller block is used to decide the torque contribution of the internal combustion (IC) engine and the electric motor. Based on the total torque request, and the characteristics of the motor, the controller decides the contribution of the electric motor. The remaining unmet torque request is supplied by the IC engine up to its maximum torque limit. If the two sources acting synergistically cannot meet the torque demand, the vehicle falls short on speed, as observed during demanding driving conditions.

SOC balancing

The state of charge (SOC) of the battery pack is an important factor in the operation of a hybrid electric vehicle. In the Honda Insight, the battery pack SOC limits are set to 20% (lower) and 80% (upper). When the battery pack reaches the lower limits of SOC (near 35%), the controller reduces the amount of assist (current flow out of the battery) by the electric motor. The reduction of "allowable assist" continues until the SOC reaches 20%, when no assist is allowed thereafter. This prevents the battery pack from damage.

Similarly, when the battery pack SOC reaches the upper limits of 80%, all regeneration by the electric motor (current flow into the battery) is stopped. This prevents the battery pack from overcharging, and damaging the system. These phenomena were observed during dyno and on-road testing of the Insight at NREL. Shown in Figure 4 is the result of this feature in the ADVISOR Insight model. It is seen that as the battery pack SOC drops, the assist capability of the motor is curtailed, and the assist current drops. Also shown in Figure 5 is the stopping of all regeneration when the SOC reaches 80%.

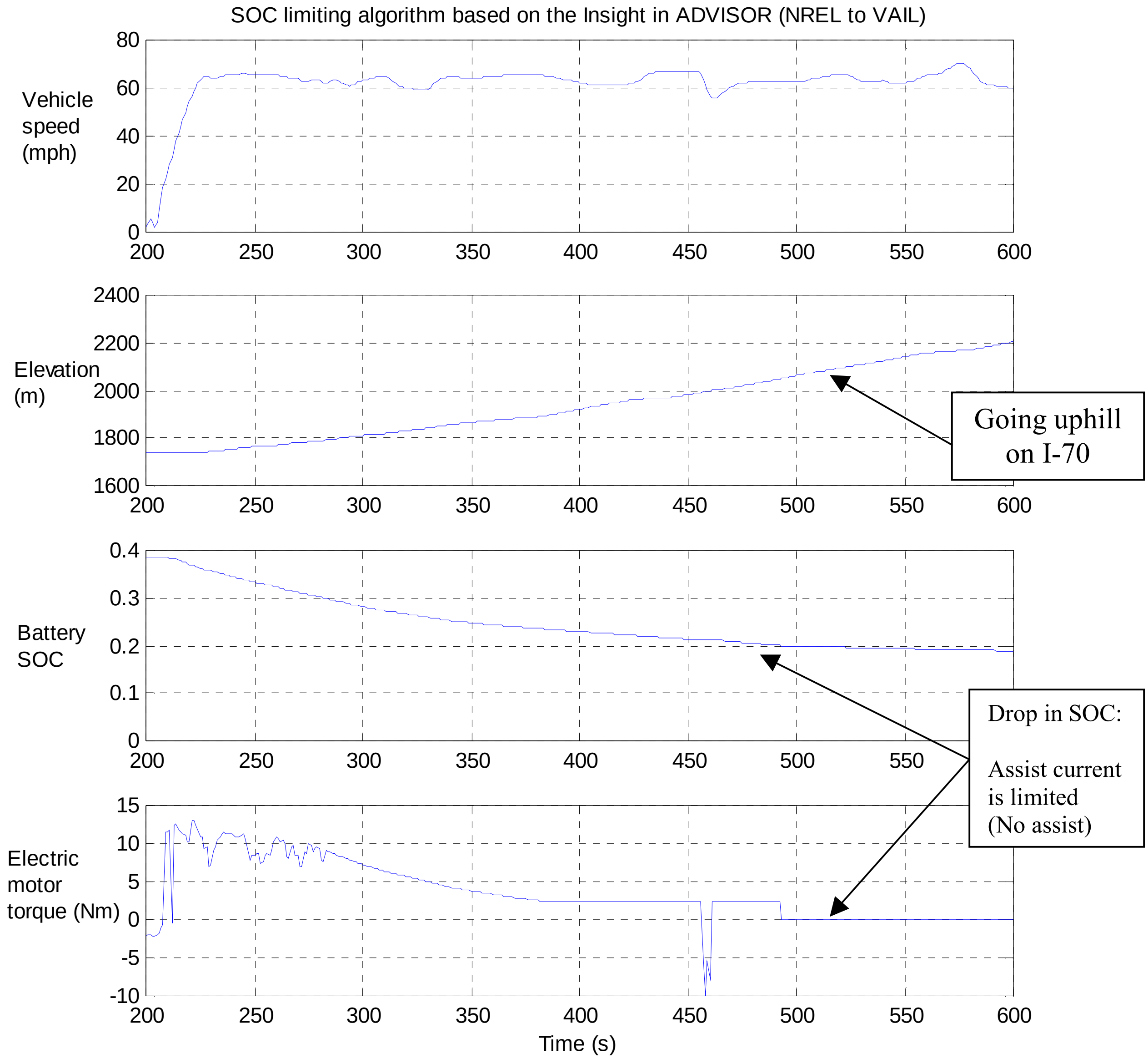


Figure 4: Effect of assist control during low battery SOC in the Insight model

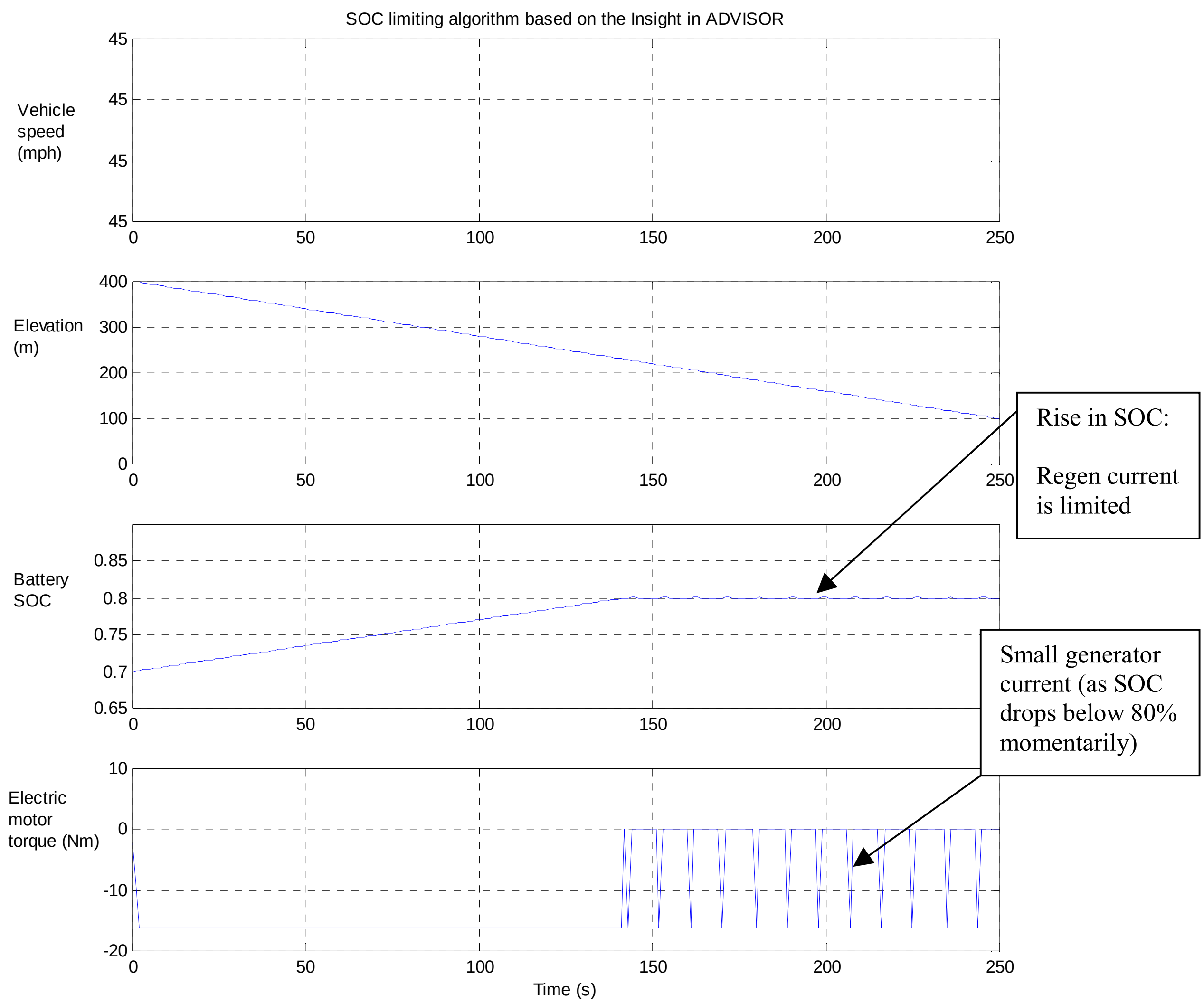
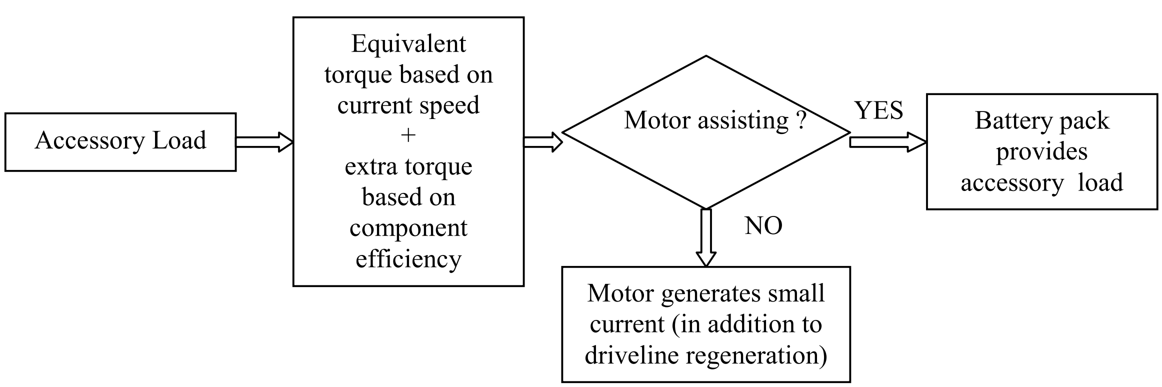


Figure 5: Effect of regen control during high battery SOC

Alternator function

As mentioned before, in the Insight the electric motor performs the function of the alternator. This is modeled in ADVISOR based on the accessory loads. The accessory load is converted to an equivalent torque request based on the instantaneous speed, and the electric motor is commanded to generate this value of torque when not assisting, or in addition to driveline regeneration.



Comparison of Data from SIMULATION and TESTING

The following parameters are considered in comparing the performance of the simulator, with the test data used for analysis.

Electric Motor Behavior

The following graphs depict the behavior of the electric motor (IMA), either performing assist, regeneration, or remaining inactive. In the following plots, the electric motor torque is plotted against time along with the speed trace, and experimental motor torque. Figures 6 through 8 show that there is very good agreement between the motor torque predicted by ADVISOR and the test data for the HWFET, UDDS and Japanese 10-15 driving cycles. Some differences are attributed to particular driver behavior or calculation difficulties (such as divide by zero).

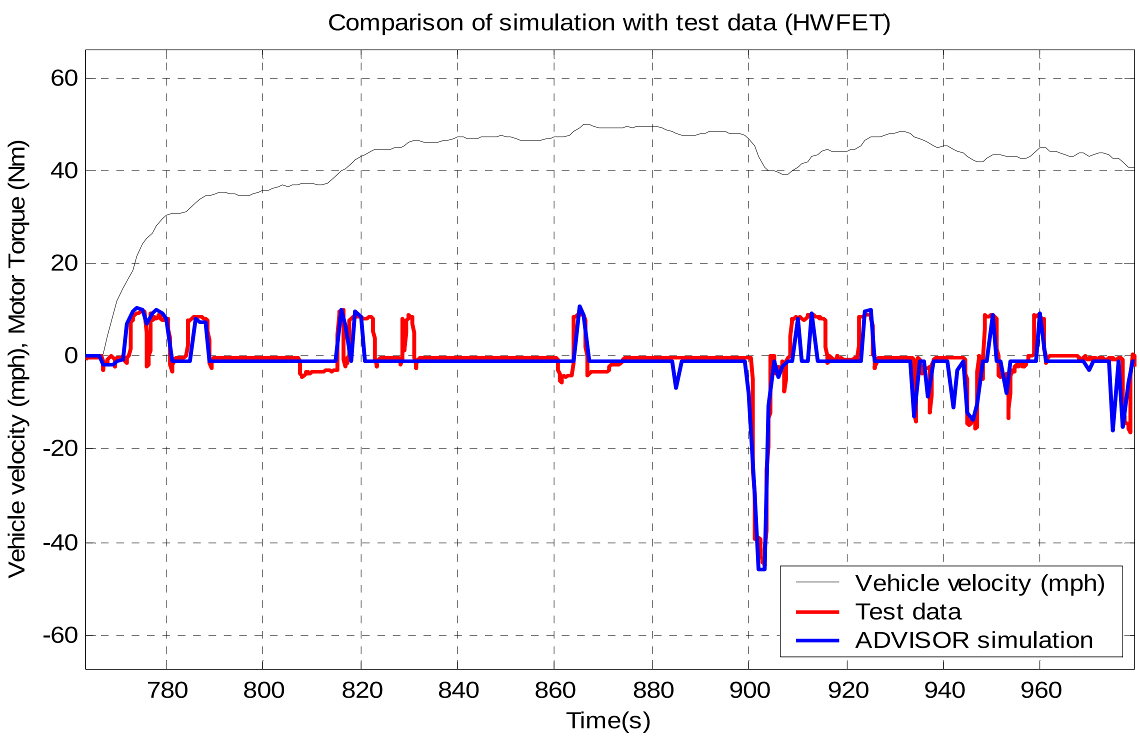


Figure 6: Comparison of motor torque with test data (HWFET)

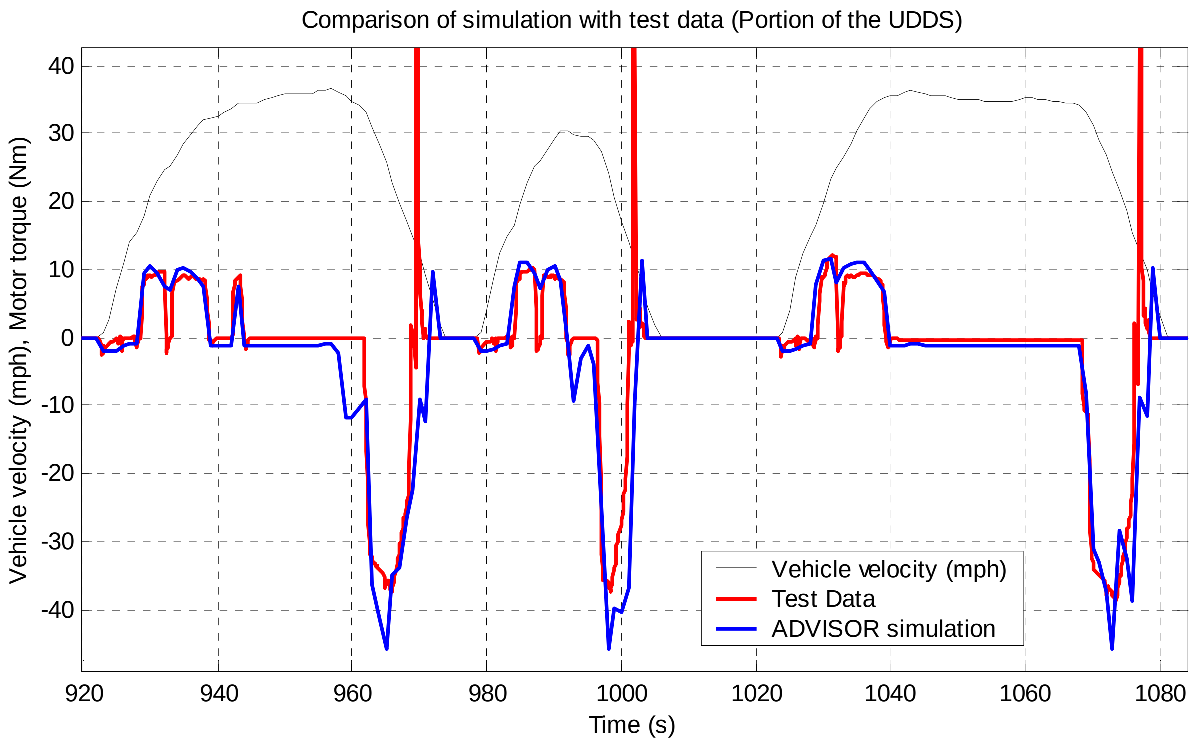


Figure 7: Comparison of Insight motor torque with test data (UDDS)

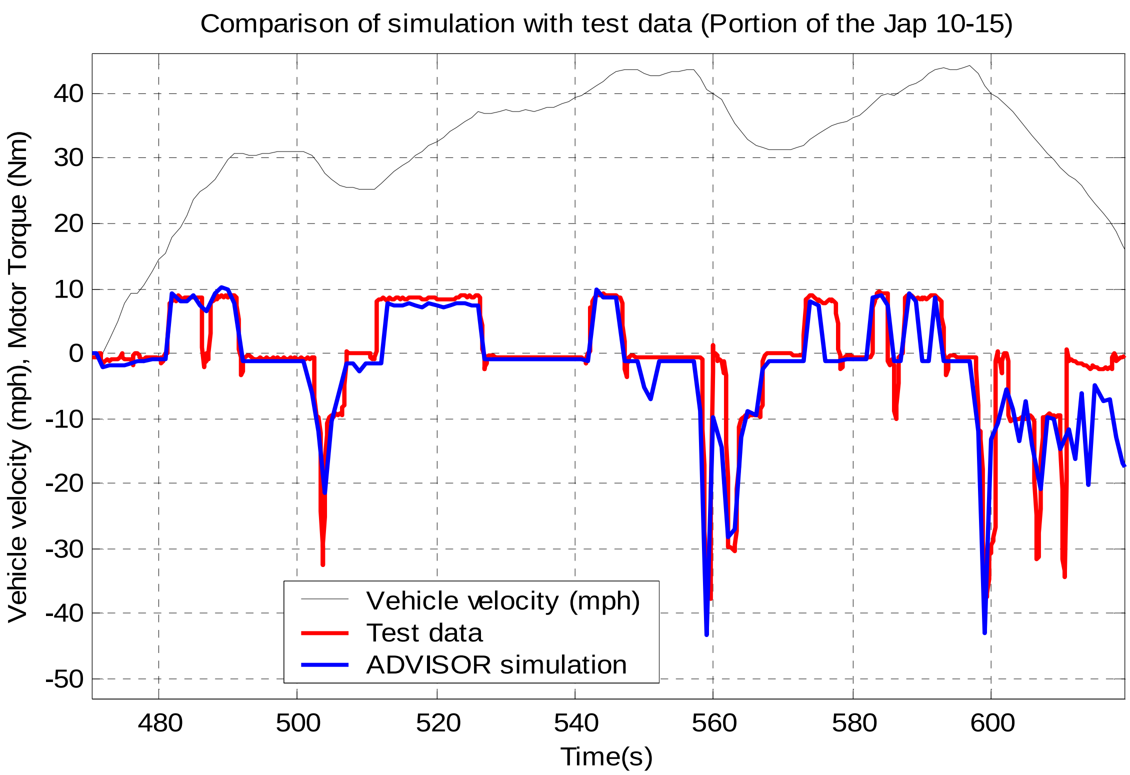


Figure 8: Comparison of Insight motor torque with test data (Jap 10-15)

Figure 9 shows a comparison of the electric motor torque contribution along with the total torque demanded from the driveline for the UDDS cycle. The figure shows the control strategy (in RED) overlaid on the test data (in BLUE). The upper right hand corner region depicts assist and the lower left corner depicts braking/regeneration.

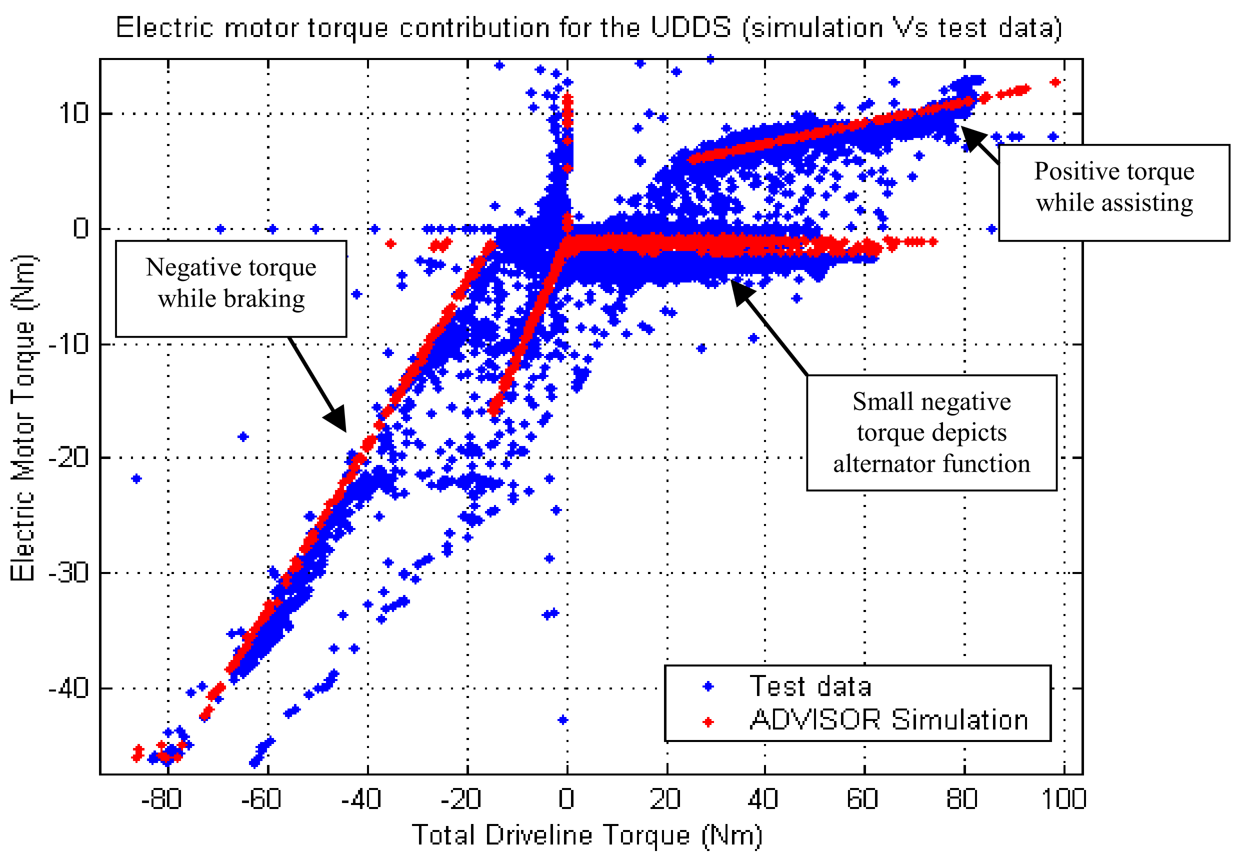


Figure 9: Comparison of the Insight motor torque with test data (UDDS)

Battery Pack State of Charge

The battery pack SOC as computed by simulation is compared with the SOC from test data. Figure 10 shows a plot of the SOC from simulation and test data for the UDDS. As explained earlier, this SOC profile is very characteristic of the Insight's battery usage. Similarly, good agreement was observed for other test cycles.

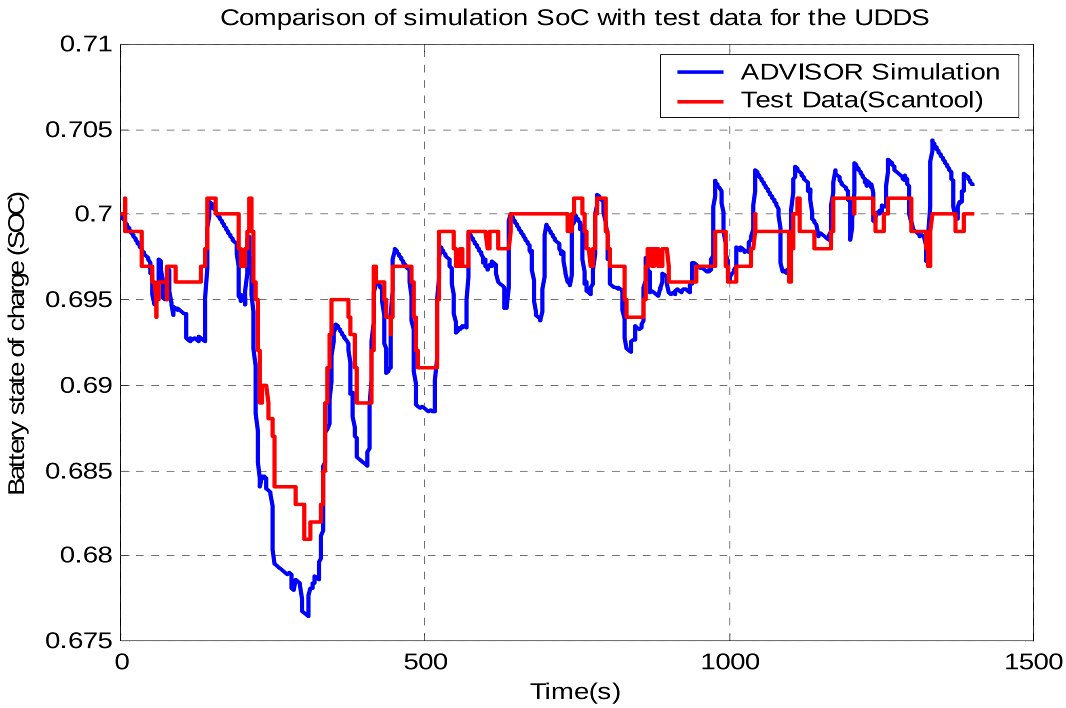


Figure 10: Comparison of Insight battery SOC with test data (UDDS)

Fuel Economy

The fuel economy obtained by ADVISOR simulation is compared with those from test data, for different driving cycles. The results are shown in Figure 11. It is seen that the simulation results closely match the fuel economy numbers from test data.

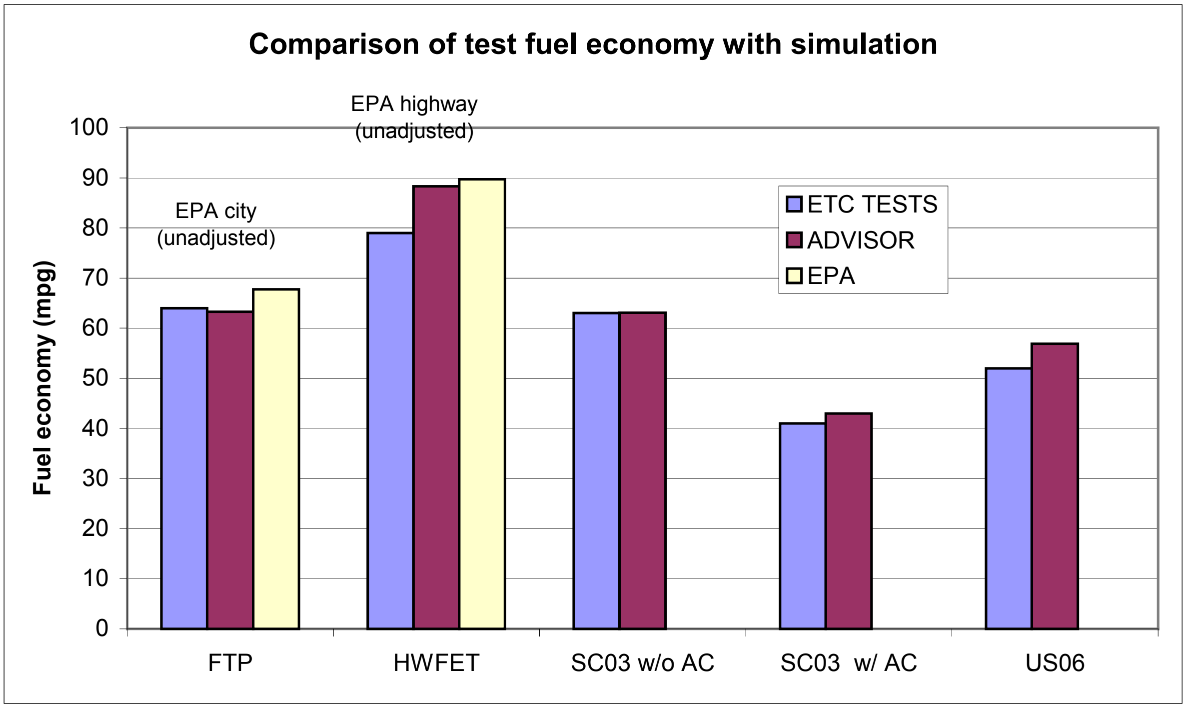


Figure 11: Comparison of Insight fuel economy with ADVISOR simulation

A summary of the Insight's fuel economy numbers from NREL's test data and ADVISOR simulation is shown in Table 2. Also listed is the fuel economy for the FTP and HWFET as published by EPA.

Table 2: Summary of Insight fuel economy from test data and simulation

	ETC TESTS	**EPA**		**ADVISOR Simulation**	
	mpg	mpg	Difference from ETC tests	mpg	Difference from ETC tests
FTP	64	67.7	5.9 %	63.3	-1.0 %
HWFET	79	89.7	13.5 %	88.3	11.7 %
SC03 w/o AC	63	n/a	n/a	63.1	0.1 %
SC03 w/ AC	41	n/a	n/a	43	4.8 %
US06	52	n/a	n/a	56.9	9.4 %

Application of the Model in ADVISOR

Scalability

Based on the Honda Insight model, a scalable new control strategy is now included in ADVISOR. This allows the user to develop his own strategy and apply it to different vehicles, based on the structure provided. The design flexibility of this strategy allows the user to vary the electric motor torque contribution for assist and regeneration, based on the torque requested from the driveline (source).

Sensitivity Analysis Based on the Insight Model

A limited sensitivity analysis was performed on the Insight model, to illustrate the potential for studying the effects of changes to the vehicle control strategy parameters and behavior of the components. The following are the results of some sensitivity analysis.

Variation of level of assist

By varying the level of assist provided by the electric motor, we can determine an optimal assist level, which does not deplete the battery pack, and increases the fuel economy of the vehicle.

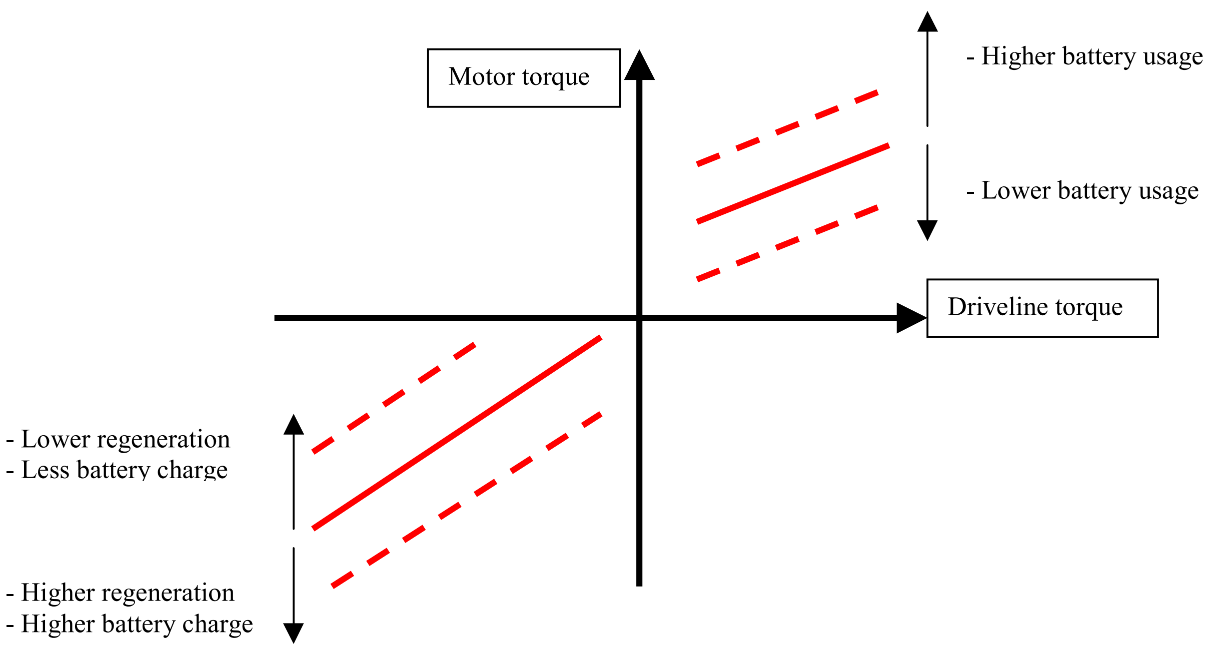


Figure 12: Variation of assist/regen using the Insight scalable control strategy

A couple of examples are illustrated below, to show the effect of varying the control strategy parameters. Table 3 shows the effect of varying the minimum electric assist of motor, as denoted by the parameter *"cs_mc_assist_min_frac."* This corresponds to using more electric motor assist during accelerations. As expected, as the electric motor is used more vigorously, the fuel economy numbers go up, and battery SOC decreases, because these are not SOC balanced runs. The result of varying the minimum electric assist on the battery SOC and fuel economy are shown in Figure 14. In the schematic below, the solid RED line in the upper right quadrant indicates the electric motor assist level.

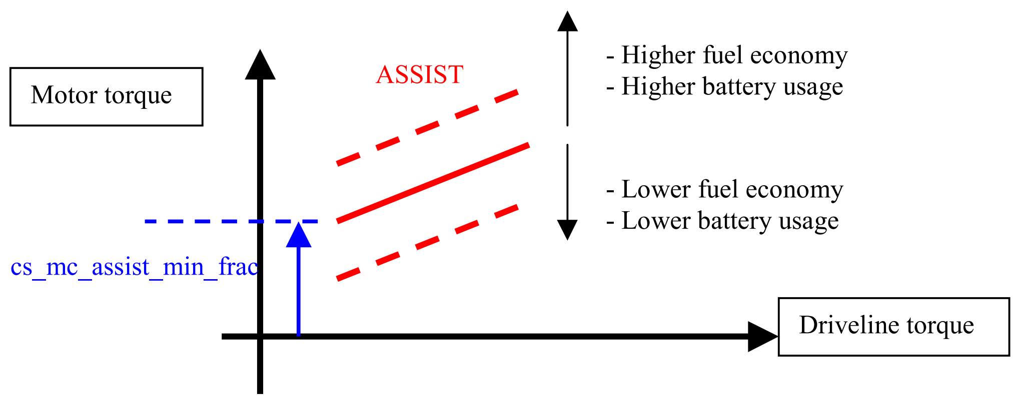


Figure 13: Variation of level of electric motor assist (Insight model)

Table 3: Effect of varying minimum electric assist (Insight model)

cs_mc_assist_min_frac	Mpg	DeltaSOC
0.05	64.1	0.039
0.17	65.8	-0.019
0.29	67.7	-0.082
0.41	69.6	-0.151
0.53	71.4	-0.229
0.65	72.4	-0.306

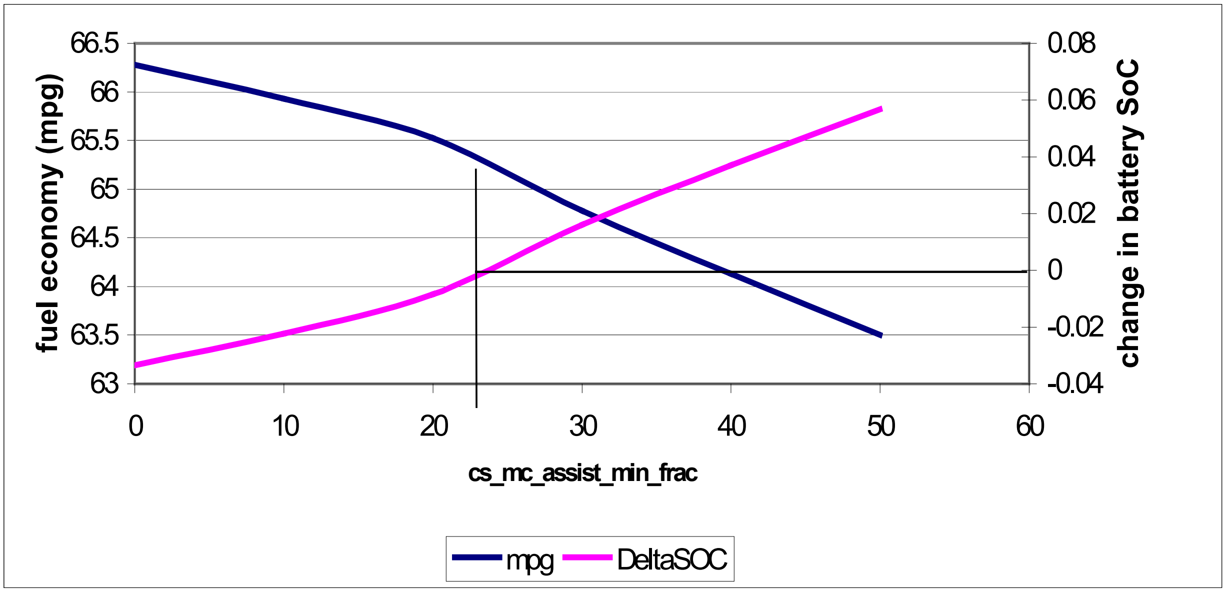


Figure 14: Effect of varying minimum electric assist (Insight model)

Another parameter that can be varied is the minimum driveline torque threshold value, above which the motor must assist the engine. The higher this value is, the greater the acceleration needs to be, before the motor provides assist. This value is denoted by the parameter *"cs_dl_assist_trq_threshold."* The effect of varying this parameter is shown in Table 4 and graphically in Figure 16.

Table 4: Effect of varying assist threshold (Insight model)

cs_dl_assist_trq_threshold	mpg	DeltaSOC
0	66.3	-0.033
10	65.9	-0.022
20	65.5	-0.009
30	64.8	0.016
40	64.1	0.037
50	63.5	0.057

In the schematic below (Figure 15), the solid RED line in the upper right quadrant indicates the electric motor assist level. As this threshold is increased, the electric motor activity is curtailed, thus using less battery charge.

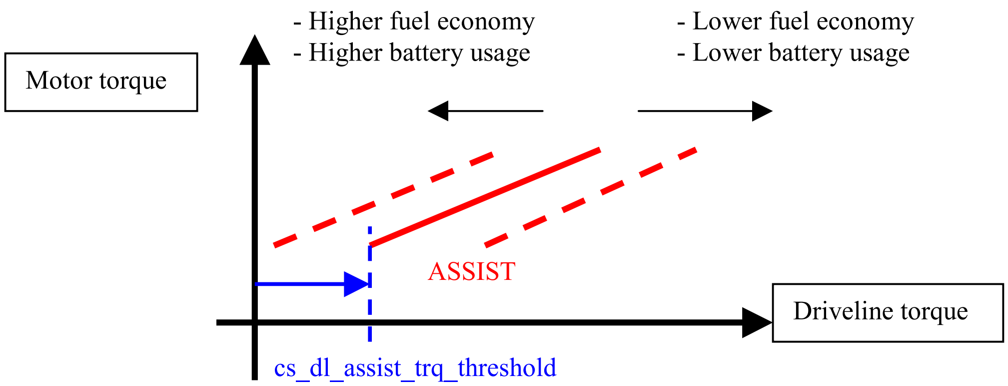


Figure 15: Variation of level of electric motor assist (Insight model)

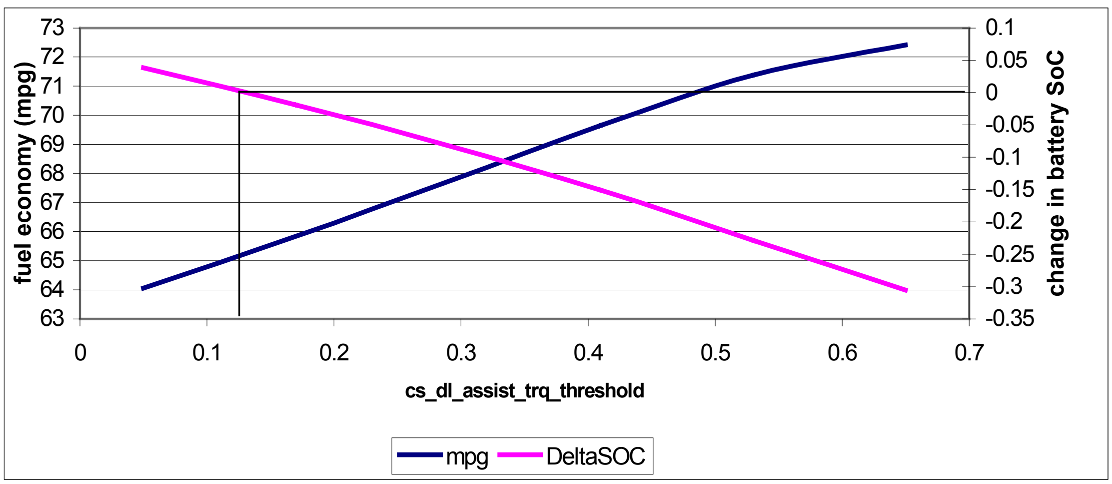


Figure 16: Effect of varying assist threshold (Insight model)

The scalable control also allows for varying the level of regeneration captured by the electric motor. This value is decided by the parameter *"cs_mc_regen_slope*." This value can be set between 0 and 1. When set to 0, the electric motor does not regenerate any negative torque seen at the driveline. When set to 1, the motor regenerates all available negative torque at the driveline. The higher this value is set, the more charge is fed into the battery pack. Table 5 shows the effect of varying this parameter. It was seen that this parameter does not affect the fuel economy much, but affects the battery SOC considerably. The higher the fraction, the higher the charge put into the battery pack. In actual design of a vehicle, the higher this parameter is, the better the capability of the drivetrain to perform regenerative braking, and prevent energy being lost solely as heat in the friction brakes. The effect of the parameter is shown graphically in Figure 18.

Table 5: Effect of varying motor regeneration fraction (Insight model)

cs_mc_regen_slope	mpg	DeltaSOC
0.4	60.94	-0.040
0.5	60.94	-0.025
0.6	60.93	-0.011
0.7	60.93	0.003
0.8	60.93	0.016
0.9	60.92	0.026

In the schematic below (Figure 18), the solid RED line in the lower left quadrant indicates the electric motor regeneration level. The higher the slope, the more negative torque is regenerated by the motor.

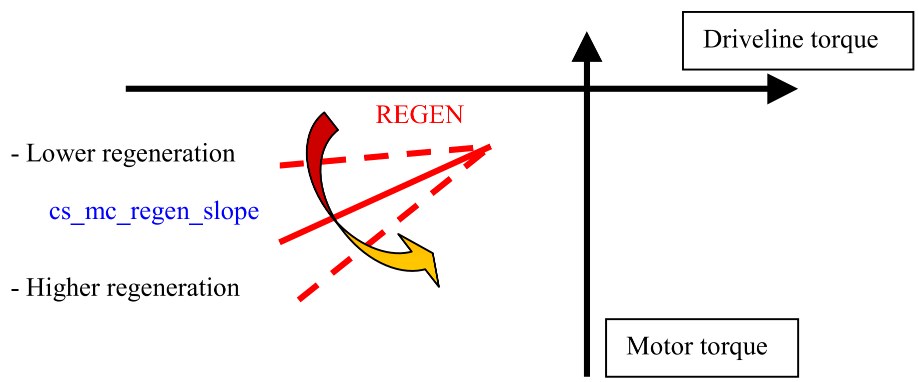


Figure 17: Variation of level of electric motor regeneration (Insight model)

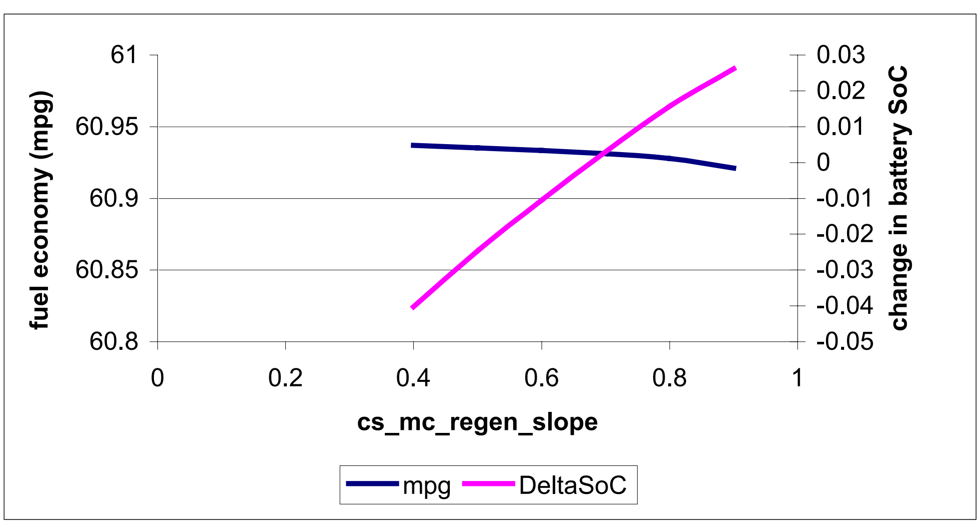


Figure 18: Effect of varying motor regeneration fraction (Insight model)

Idle stop feature

The idle stop feature (which allows the engine to shut off during a vehicle stop) can be disabled in simulation by the variable *"vc_idle_bool."* The following table describes the benefits of the feature (in the Insight), and it's effects on fuel economy and battery SOC. Here, we see in Table 6 that by using ADVISOR to eliminate the idle-stop feature results in a 6.5% decrease in fuel economy with only a limited change in battery SOC. The Battery SOC decreases, since there is no regeneration during the idling process.

Table 6: Sensitivity of the scalable model

Parameter	Idle stop OFF	Idle stop ON	Effect of adding idle stop (ON)
Fuel economy (on the UDDS)	56.9 mpg	60.9 mpg	Increase of approx. 6.5%
Battery SOC (on the UDDS)	Small net positive charge into battery during idle	No net charge into the battery during stops	Moderate drop in SOC OFF – SOC gain = 1.88% ON – SOC gain = 0.3%

The following plot (Figure 19) shows the effect of the engine idle-stop feature on the engine operation.

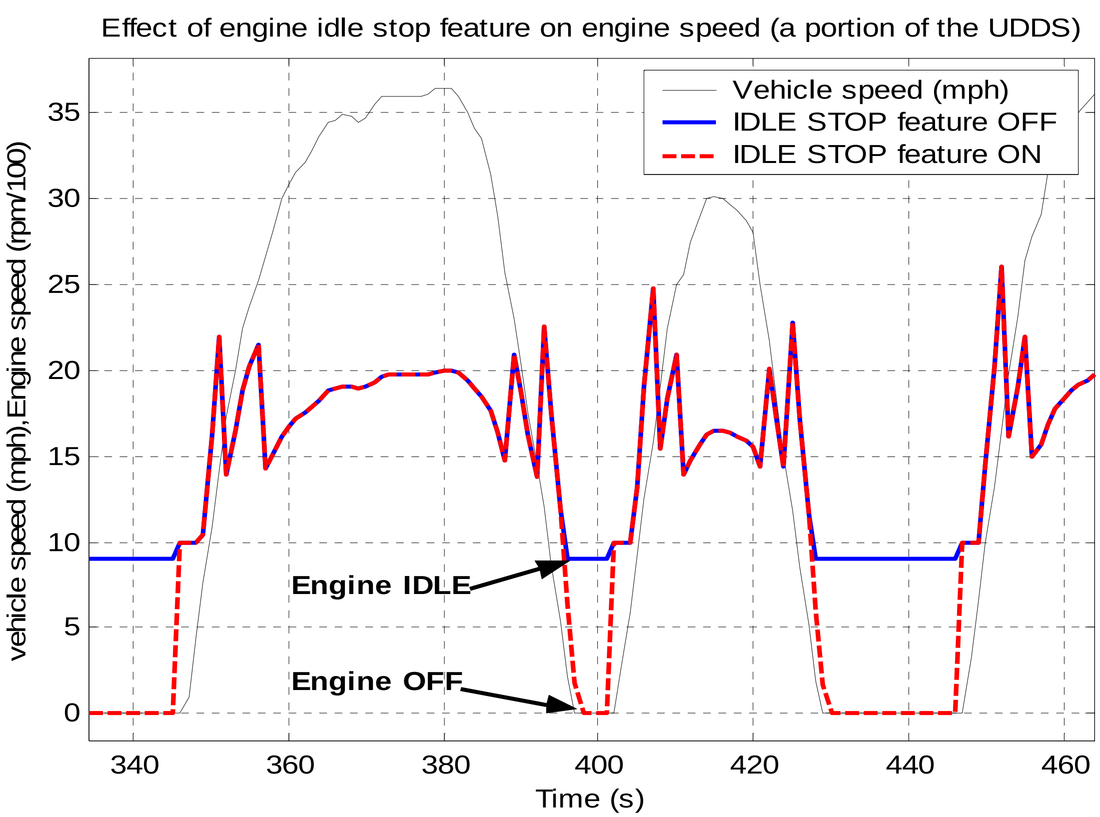


Figure 19: Engine idle-stop feature in simulation